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海洋微塑料污染的生态效应研究进展

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摘要:海洋微塑料污染已成为全球性环境问题。微塑料粒径小,易与海洋生物发生相互作用,可通过多种途径进入海洋生物体内,并在其组织和器官中蓄积和转移,对机体产生毒害。微塑料可沿食物链进行传递,威胁海洋生态系统的健康与稳定。因此,海洋生物与微塑料的相互作用以及海洋微塑料污染的生态效应成为当前研究的热点。综述微塑料的生物附着、生物摄入、对海洋生物的毒性效应及其与化学污染物的复合毒性效应研究的基础上,提出未来微塑料生态效应研究应重点关注我国海洋环境中微塑料的污染现状及生物摄入状况、微塑料的生物效应及其毒理学机制研究、微塑料与其他污染物的复合效应、以及微塑料在海洋生态系统中的作用及其生物地球化学行为等。

关键词:微塑料;生态效应;海洋环境污染;复合毒性

Research advances on the ecological effects of microplastic pollution in the marine environment

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Abstract: Microplastic contamination of the marine environment has become a global environmental problem. Because of their small dimensions, microplastics can easily interact with a wide range of marine organisms, enter their bodies in various ways, and accumulate in and transfer between their tissues and organs, which results in toxic effects. Absorption and ingestion of microplastics, primary by lower trophic-level organisms, can be transferred along the marine food chain, threatening marine ecosystem health and stability. For this reason, the interaction between marine organisms and microplastics, and the ecological effects of marine microplastic pollution have become hotspots for current studies. Based on the review of biofouling of marine organisms on the microplastic surface, ingestion of microplastics, toxic effects of microplastics on marine organisms, and the combined toxic effects of microplastics with other chemical contaminants, this study proposed that future research on the ecological effects of microplastic pollution should focus on marine organism ingestion of microplastics in the marine environment of China, biological effects and toxicological mechanisms of microplastics on organisms, combined effects of microplastics with other contaminants, and the functions of microplastics in the marine ecological system and their biogeochemical behaviors.

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塑料具有优良的物理化学特性,被广泛应用到多个领域,自 20 世纪 40 年代大规模生产以来,其全球生产量和使用量急剧上升,2013 年全世界塑料产量已经接近 3 亿 t[1]。生产生活中未被有效处置的塑料垃圾会以碎片或微粒的形式进入海洋[2-3],并随海洋动力过程进行远距离迁移,导致全球范围内的海洋塑料污染[2, 4-7]。据估算,目前全世界海洋漂浮的塑料碎片超过 5 万亿个,重量在 25 万 t 以上[8],每年给海洋生态系统造成的经济损失高达 130 亿美元[9-10]。

通常将环境中粒径<5 mm 的塑料颗粒称为微塑料[11]。微塑料的化学性质稳定,可在环境中长期存在[3],被认为是一种新型环境污染物[12]。海洋环境中的微塑料可分为初生微塑料和次生微塑料。初生微塑料是指工业生产过程中起初就被制备成为微米级的小粒径塑料颗粒,比如牙膏和化妆品中添加的塑料微珠等[13];次生微塑料则指大型塑料碎片在环境中分裂或降解而成的塑料微粒[14]。海洋环境中常见微塑料的化学组成主要有热塑性聚酯(Polyester, PET)、高密度聚乙烯(High-density polyethylene, HDPE)、聚氯乙烯(Polyvinyl chloride, PVC)、低密度聚乙烯(Low-density polyethylene, LDPE)、聚丙烯(Polypropylene, PP)、聚苯乙烯(Polystyrene, PS)、聚酰胺(Polyamide, PA)等[15]。

微塑料在海洋环境中会发生一系列的迁移和转化(图 1)[16]。微塑料密度低于海水,进入海洋环境中会漂浮或悬浮在海水中,在洋流、潮汐、风浪、海啸等动力过程驱动下进行扩散[17-20]。海浪和潮汐还会驱使微塑料在海岸地区沉积[3, 12]。在海洋环境的长期作用下,具有疏水性的微塑料表面特征变得复杂,很容易吸附一些有机和金属类化学污染物,并且还会附着一些黏土颗粒、有机碎片、海藻、微生物等,这些过程会增大微塑料颗粒的密度或改变其表面特性,促使其发生沉降[3, 21-22]。在海洋环境中,长期的物理、化学和生物共同作用会将微塑料分裂成更小的纳米级颗粒[3, 15, 23]。在太阳辐射、海洋生物和海水等的作用下,微塑料会发生光降解、生物降解、氧化分解和水解等降解和转化过程[15-16]。此外,微塑料还会被海洋生物摄入体内,并随之迁移,成为与海洋生物网连接的纽带[16]。

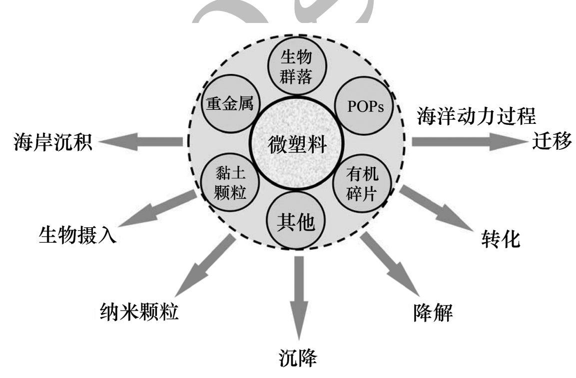


图 1 微塑料在海洋环境中的行为(改自参考文献[16])

Fig. 1 Behaviors of microplastics in the marine environment (revised from reference[16])

海洋环境中微塑料的大范围污染会对海洋生物的生存造成威胁。最新研究表明,微塑料会损害太平洋牡蛎(*Crassostrea gigas*)的生殖健康[24],还会对仔鱼的生长发育、食性、行为活动等造成不良影响[25]。生物是生态系统的重要组成部分,微塑料对海洋生物生存造成的负面影响会威胁海洋生态系统的健康与稳定,海洋生物体中微塑料的污染状况以及微塑料的生态效应已成为当前应着重关注的问题[26]。为此,本文从微塑料的生物附着、生物摄入、生物毒性效应以及与化学污染物的复合毒性方面综述了海洋微塑料污染的生态效应研究进展,并提出了未来的研究重点。

1 生物附着

海洋环境中的微塑料颗粒可成为微生物和藻类等生物附着生长的载体[27]。微塑料进入海洋环境后,微生物会快速附着在其表面,一周左右便可形成牢固附着的生物膜[28]。Zettler 等[29]利用扫描电子显微镜和新一代基因测序技术分析发现,北大西洋近岸水体中附着在微塑料上的微生物群落包括异养生物、自养生物、共生生物等。科学家估算附着在海洋塑料碎片上的微生物总量高达(1000—15000) t[30]。法国海湾水体的调查结果显示,平均约 22% 的微塑料颗粒样品表面附生有小型海藻和有孔虫类,其中夏季样品附着的比例

更高[31]。

有害生物的附着会让微塑料充当“移民”工具。微塑料化学性质稳定,在海洋环境中很难被降解,并在海洋动力过程作用下可远距离迁移。微塑料被生物附着后就成为生物传播的载体,当附着有生物的微塑料跨生物地理区系迁移,就会导致生物入侵[32-33]。

生物附着会影响微塑料在海洋环境中的迁移。微塑料表面形成生物膜后,其疏水性减弱,亲水性显著增强,并且塑料颗粒的密度也逐渐增大,会由水体表面向水下沉降,这也是导致微塑料在海底沉积的重要因素[3, 22, 28]。

微塑料的生物附着极其复杂,季节变化、地理位置、水温、海水营养状况、底质类型、水流速度等都会影响生物在微塑料表面的附着[22]。

2　生物摄入

生物摄入是海洋微塑料进入食物网的重要途径。海洋环境中的微塑料很容易被大多数海洋生物,如浮游动物、底栖生物、鱼类、海鸟、海洋哺乳动物等摄入体内(图 2)。首先,海洋生物摄入微塑料与其摄食和呼吸方式有关,微塑料的粒径较小,海洋生物的摄食方式很难将微塑料与食物分离开来[34],而利用鳃孔呼吸的海洋生物(如蟹类)还可通过呼吸过程将微塑料吸入鳃室,这些微塑料可在其鳃室富集,但不会进入其他组织或器官[35];其次,海洋生物会误食微塑料,海洋中的微塑料与浮游生物的大小和密度相似,容易被海洋生物误判为食物而主动捕获[36]。微塑料可沿食物链进行传递[37-38],低营养级生物体内的微塑料通过捕食作用进入到高营养级生物体内。被海洋生物体摄入体内的微塑料颗粒可在其组织和器官中转移和富集,许多海洋生物的胃、肠道、消化管、肌肉等组织和器官甚至淋巴系统中均发现有微塑料存在[39]。

2.1　浮游动物

浮游动物利用化学与机械感受器相结合的方式选择特定食物如藻类或其他颗粒物等[40-41],这就为微塑料的摄入提供了可能。浮游动物的种类、生命阶段、摄食模式和消化器官的解剖学特征等均会影响其对微塑料的摄入[38, 42-44]。此外,微塑料的粒径、丰度、环境行为也会影响浮游动物的暴露风险[38, 42-44]。一些浮游动物还会根据颗粒物的表面特性及带电荷情况选择捕获物[42],从而增加微塑料的摄入可能。室内实验和野外调查结果均证实浮游动物可以摄入微塑料。培养实验研究结果显示,东北大西洋常见的 13 种浮游动物可以摄入粒径为(1.7—30.6) μm 的聚苯乙烯塑料颗粒[42]。野外调查结果也表明,北太平洋冠新哲水蚤(*Neocalanus cristatus*)和太平洋磷虾(*Euphausia pacifica*)的体内均存在微塑料颗粒,并且其粒径范围(≤ 2000 μm)远大于培养实验(<50 μm)[45]。微塑料被浮游动物摄入后,一部分会在生物体内蓄积,另一部分可随粪便排出体外[42]。

2.2　底栖动物

底栖动物门类众多,栖息方式和摄食模式多样。沉积在海底的微塑料可被底栖动物摄入体内[2, 46]。室内培养实验结果显示,滤食性贻贝(*Mytilus edulis*)和渣食性沙蚕(*Arenicola marina*)等底栖动物可非选择性地摄入微塑料[23, 47],而海参则可利用触手选择性地摄入微塑料颗粒[48],其中滤食性双壳贝类逐渐成为研究海洋生物对微塑料摄入的模式动物[24, 49-50]。微塑料可在底栖食物链中传递。以双壳贝类为食的螃蟹可通过捕食体内含有微塑料的贻贝而间接地摄入微塑料[35]。此外,底栖动物摄入微塑料的途径有多种,滨蟹(*Carcinus maenas*)和贻贝不仅可经口摄入微塑料,还可以利用其鳃孔吸入微塑料[35, 50]。野外调查结果发现底栖动物体内普遍存在微塑料。例如,野生褐虾(*Crangon crangon*)[39]和养殖贝类[51-52]的消化系统中发现有微塑料,北太平洋海域采集的 33.5%的鹅颈藤壶(*Lepas* spp.)胃肠道中检测出微塑料[53],还有研究指出挪威龙虾(*Nephrops norvegicus*)肠胃中的塑料纤维丝主要来源于渔网[54]。

摄入底栖生物体内的微塑料同样会在其组织或器官中转移和富集。聚甲基丙烯酸甲酯(29.5±26) μm 被带丝蚓(*Lumbriculus variegatues*)摄入后可进入其肠道系统[55]。粒径小于 16 μm 的微塑料可在贻贝的肌肉



图 2　海洋环境中微塑料的生物摄入及生物链传递（改自参考文献[39]）

Fig.2　Microplastic ingestions by organisms and trophic transfer in the marine environment（revised from references[39]）

组织中富集,并会转移到淋巴系统[49]。高密度聚乙烯(HDPE)微塑料可以通过贻贝的肠胃系统进入其组织甚至细胞中[50]。底栖生物对摄入体内的微塑料还具有一定的回避或排斥作用。微塑料进入消化系统后,机体可通过生成"假粪"将其排泄出来,这种形式需要消耗额外能量,会导致饥饿[47]。还有一部分底栖生物,如沙蚕、海胆(*Tripneustes gratilla*)和海参可以通过肠道不受损害地排泄出不被机体吸收的微塑料[23, 45, 48]。

2.3 游泳动物

2.3.1 海洋鱼类

海洋鱼类对微塑料的摄入以主动摄食为主,通过吸食、捕食、咬食、吞食等方式摄食悬浮在水体中的微塑料颗粒。早在 20 世纪 70 年代就有报道称美国和英国沿海捕获的野生鱼类体内有微塑料存在[39]。室内培养实验显示,鱼类在早期生活阶段会摄入(100—500) μm 微塑料颗粒[56],误食是鱼类对微塑料摄入的主要途径,鱼类的体型越大,摄入的微塑料粒径也越大[57]。近海和远洋的上层、中层和底层鱼类均会摄入微塑料。河口和近岸海域有陆源河流污染输送,容易受到微塑料污染[58],在河口区采集的 23%的野生海鲶(*Cathorops* spp. 和 *Sciades herzbergii*)和 7.9%的石首鱼(*Stellifer* spp.)体内检测到微塑料[59-60]。在北海和波罗的海采集的上层和底层鱼类,5.5%的个体肠道中发现有塑料颗粒存在[61],而在菲律宾海采集的底层鱼类的胃肠中发现存在微塑料的个体比例高达 40%[62]。北大西洋采集的中层鱼类,9%的个体体内发现有塑料碎片和塑料纤维[63]。此外,采自英吉利海峡的 10 种鱼类中,摄入微塑料的个体比例也高达 36.5%[64]。由此可见,鱼类对微塑料的摄入情况已经成为反映海洋微塑料污染的重要指标。

2.3.2 海洋哺乳动物

海洋哺乳动物体型很大,可以通过滤食、呼吸或者捕食体内含有微塑料生物的方式将微塑料摄入体内,比如须鲸进食过程中过滤海水时[65],会附带地将微塑料挡在口内,这种捕食模式使得须鲸直接摄入微塑料的概率要大于齿鲸或喙鲸[66]。在海豹(*Phoca vitulina*)体内也发现有微塑料的存在,其胃、肠中存在微塑料的个体数分别占总个体数量的 11%和 1%[67]。海洋鲸类动物虽然被认为是海洋污染的指示物种[68-69],但是由于其体积大、消化快,又多属濒危珍稀物种,给采样和研究带来很大困难,因此有关鲸类对微塑料的摄入研究较少[39]。Fossi 等[70-71]通过分析搁浅的长须鲸(*Balaenoptera physalus*)脂肪中邻苯二甲酸的浓度来指示其对微塑料的摄入情况,但是这种指示结果存在一定问题,并且鲸类搁浅十分罕见,具有不可预见性。海洋哺乳动物还可能通过被捕食生物的食物链传递而摄入微塑料。例如,海豹(*Arctocephalus* spp.)排泄物中发现的微塑料可能来自其摄食的鱼类(*Electrona subaspera*)体内[72]。

2.3.3 海洋爬行动物

海洋爬行类动物对微塑料的摄入与其取食方式有关[73],通过食物链传递摄入微塑料是一种重要途径。比如蠵龟(*Caretta caretta*)、平背龟(*Natator depressa*)和肯氏龟(*Lepidochelys kempii*)以甲壳动物、软体动物、鱼类、海藻等为食[48-49, 74],可通过捕食体内含有微塑料的被捕食生物而摄入微塑料。棱皮龟(*Dermochelys coriacea*)常以水母为食[74],而有些微塑料的形态与水母非常相似,因此海龟还可能会直接误食微塑料,草食性绿海龟(*Chelonia mydas*)胃中存在的塑料微粒[75]也可能与其直接误食有关。已有研究显示,海龟可以摄入粒径较大的塑料制品[73,76],但是关于其对微塑料的摄入研究还很少。

2.3.4 其他

有报道称,生活在水下 200—700 m 深的大型头足类动物茎柔鱼(*Dosidicus gigas*)的胃中也发现有微塑料的存在[77],而其摄入途径目前还不清楚,有可能是直接摄入了沉入水下的微塑料,或者是捕食了体内摄入微塑料的生物体。

2.4 海洋鸟类

海洋鸟类的摄食方式主要分为水面摄食和潜食两类,其摄入微塑料的途径主要包括误食、食物链传递以及母鸟反刍[78]。野生管鼻鹱(*Fulmarus glacialoides*)、海燕(*Puffinus tenuirostris*)、剪水鹱(*Calonectris diomedea*)、信天翁(*Thalassarche melanophris*)等近 50 种鹱形目动物的肠胃中都检测出了微塑料,并且在鸟类的食物、反刍物和粪便等相关样品中也都检测到了微塑料[39]。一些海鸟比如灰翅鸥(*Larus glaucescens*)可以从它们的消化道以反刍的形式去除微塑料[79]。但是这也意味着海鸟会通过反刍喂食幼鸟将微塑料传递给下一代,比如暴风鹱(*Fulmarus glacialis*)幼鸟肠道中的塑料含量明显多于成鸟[80]。工业原料颗粒和塑料制品(塑料用品)碎片是海鸟摄入微塑料的两种主要类型[81-82]。有学者对鸟类摄入微塑料的类型和总量进行了研

表 1 微塑料的生物效应研究

Table 1 Studies of the biological effects of microplastic

受试物种 Organism	微塑料尺寸 Size	微塑料类型 Types	暴露剂量 Exposure dose	复合污染物 Combined pollutants	毒性效应指标 Toxic effect	参考文献 References
环节动物 Phylum Annelida						
沙蚕 *Arenicola marina*	130 μm	UPVC	0—5%（质量比）		摄食量	[86]
	230 μm	PVC	1500 g 沉积混合物		氧化胁迫	[87]
	400—1300 μm	PS	0,1,10,100 g/L		摄食活性、生长	[88]
软体动物 Phylum Mollusca						
贻贝 *Mytilus edulis*	0—80 μm	HDPE	2.5 g/L		免疫反应、溶酶体膜稳定性	[50, 89]
紫贻贝 *Mytilus galloprovincialis*	<100 μm	PE,PS	1.5 g/L	PAHs	免疫反应、氧化应激反应、神经毒性效应、基因毒性等	[90]
太平洋牡蛎 *Crassostrea gigas*	2,6 μm	PS	0.023 mg/L		生长发育、生殖细胞质量	[24]
节肢动物 Phylum Arthropoda						
日本虎斑猛水蚤 *Tigriopus japonicus*	0.05, 0.5, 6 μm	PS	9.1×10^{11}个/ mL; 9.1×10^{8}个/ mL; 5.25×10^{5}个/ mL		致死率、生长发育、繁殖能力	[91]
桡足类 *Calanus helgolandicus*	20 μm	PS	75 个/ mL		摄食量、死亡率、卵形态及孵化率	[92]
端足虫 *Hyalella azteca*	10—27 μm	PE	0—20000 个/ mL		死亡率、生殖、生长	[93]
	20—75 μm	PP	0—90 个/ mL			
脊索动物 Phylum Chordata						
鰕虎鱼 *Pomatoschistus microps*	1—5 μm	PE	18.4, 184 μg/L	PAHs	死亡率、生物酶活性	[94]
	420—500 μm	PE	100 个/L		捕食行为	[95]
	1—5 μm	PE	0.216 mg/L	Cr(VI)	捕食行为、生物酶活性	[96]
日本青鳉鱼 *Oryzias latipes*	3 mm	LDPE	10% 摄食量	PAHs, PCBs, PBDEs	肝脏毒性	[97]
	<1 mm	PE	慢性毒性剂量		基因表达、内分泌干扰毒性	[98]
海鲈鱼 *Dicentrarchus labrax*	10—45 μm	PE	10^4,10^5个/ g		死亡率、基因表达	[99]
斑马鱼 *Danio rerio*	1—5 μm	未公布	0.5 mg/(70 mL)	PAHs	7-乙氧基-异吩 唑酮-脱乙基酶(EROD)活性	[100]
	10—20 μm	PE	2.5 mg/(70 mL)			
鲈鱼 *Perca fluviatilis*	90 μm	PS	10000 个/m^3; 80000 个/m^3		卵孵化率、生长速率、运动性、回避行为	[25]
棘皮动物 Phylum Echinodermata						
海胆 *Tripneustes gratilla*	10—45 μm	PE	1, 10, 100, 300 个/ mL		存活率、生长状况	[44]
海胆 *Lytechinus variegatus*		PE			胚胎发育	[101]

UPVC(Unplasticised polyvinylchloride):未增塑聚氯乙烯; PVC(Polyvinyl chloride):聚氯乙烯; HDPE(High-density polyethylene):高密度聚乙烯; PE(Polyethylene):聚乙烯; PS(Polystyrene):聚苯乙烯; PP(Polypropylene):聚丙烯; LDPE(Low-density polyethylene):低密度聚乙烯

究,结果显示,20 世纪 70 年代以后,海洋鸟类摄入微塑料的类型逐渐从工业原料向塑料用品转变[83-84]。鸟类已经成为监测海洋微塑料污染的指示生物[85]。

3 微塑料的毒性效应

室内培养试验已经取得了微塑料对部分生物个体的毒性效应研究结果(表 1),主要包括微塑料对生物体的存活率、生长发育、行为活动、生殖状况、基因表达等方面的影响。微塑料的毒性效应与其材质类型、尺寸大小、暴露剂量等有密切联系,并且受试物种的差异也非常显著。本文将微塑料对海洋生物的毒性效应概括为 6 个方面。

3.1 致死效应

微塑料暴露可导致海洋生物的存活率降低、死亡率升高。端足类美洲钩虾(*Hyalella azteca*)暴露在 10—27 μm 聚乙烯微塑料和 20—75 μm 聚丙烯微塑料中显示出明显的剂量-效应关系,随着微塑料暴露剂量的上升,钩虾的死亡率也逐渐升高,并得出聚乙烯和聚丙烯微塑料对钩虾的 10 d 半数致死浓度(LC_{50})分别为 4.6×10^4个/mL 和 71 个/mL[93]。海鲈鱼(*Dicentrarchus labrax*)的死亡率随着 10—45 μm 聚乙烯微塑料暴露剂量的增加从 30%左右显著上升至 44%[99]。慢性毒性效应研究显示,0.05 μm 和0.5 μm的聚苯乙烯微球对日本虎斑猛水蚤(*Tigriopus japonicus*)的致死率随着暴露剂量的增加而显著上升[91]。棘皮动物(*Tripneustes gratilla*)幼体存活率在 300 个/mL 的 10—45 μm 聚乙烯微塑料暴露剂量下明显降低[44]。

3.2 生长发育毒性

微塑料摄入会对生物体的生长发育产生负面影响。与对照组相比,暴露于微塑料环境中的鱼类受精卵孵化率明显下降,仔鱼的体长也有所降低[25]。沙蚕体重降低程度与沉积物中聚苯乙烯颗粒 40—1300 μm 的浓度正相关[88]。Kaposi 等[44]将海胆暴露在不同浓度的聚乙烯微球中,结果显示,暴露的浓度越高,海胆对微球的摄入量越多,海胆的体形越小。微塑料被海洋生物摄入体内后会在生物体的消化道中积累并阻塞消化道[43,49,55],动物因此会产生饱腹感,其摄食量或摄食速率下降,导致体内能量储备减少[86],机体生长所需能量来源补充不足[35],从而影响生物体的生长发育。

3.3 行为毒性

微塑料的摄入可以影响生物个体的行为特征。Lönnstedt 和 Eklöv[25]的研究显示,仔鱼喜好捕食微塑料颗粒,微塑料的暴露会让鲈鱼(*Perca fluviatilis*)仔鱼的嗅觉灵敏性和活动能力变差,面对外来刺激时其反应变得迟钝。当把捕食者引入到仔鱼生存的环境中,对照组中仔鱼仍然有近半数存活,而微塑料暴露组中的仔鱼则无一幸存[25]。桡足类汤氏纺锤水蚤(*Acartia tonsa*)幼体暴露在 45 μm 的塑料微球中,其游泳行为会受到影响,并且会出现“跳跃”反应[102]。还有研究表明,微塑料暴露会严重影响生物体的正常摄食行为[42, 56,93]。

3.4 生殖毒性

微塑料会损害生物个体的生殖健康。暴露在微塑料中的雌性牡蛎产生的卵母细胞个数和大小均显著小于对照组,雄性产生的精子活动速率显著低于对照组,子代幼体的生长速率也明显慢于对照组[24]。暴露在 0.5 μm 和 6 μm 的聚苯乙烯微球中,日本虎斑猛水蚤的繁殖能力显著下降[91]。哲水蚤(*Calanus helgolandicus*)在 20 μm 的聚苯乙烯微塑料中暴露 6 d 后,虽然其产卵量没有受到显著影响,但是卵的尺寸明显缩小,孵化成功率显著下降[92]。导致这个结果可能与两方面因素有关:第一,微塑料通过干扰生物体的消化过程而降低生殖系统的能量分配,从而降低生殖细胞质量;另外,微塑料会产生内分泌干扰作用,损害生物体的生殖健康[24],比如有研究发现,暴露在聚乙烯微塑料中的日本青鳉鱼(*Oryzias latipes*)雄性个体生殖细胞出现了异常生长现象,表现出卵母细胞的特征,而非精原细胞特征[98]。

3.5 免疫毒性

进入生物体内的微塑料,可通过在组织和器官的转移与富集进入机体免疫系统,对生物体产生免疫毒性。粒径小于 16 μm 的微塑料会转移到贻贝淋巴系统[49],粒径小于 80 μm 的高密度聚乙烯微塑料可在贻贝消化

系统中富集,导致血流粒细胞增多和溶酶体膜不稳定等,引发机体免疫系统的炎症反应[50]。微塑料的免疫毒性主要受其物理性状诱导,表面形状不规则的微塑料颗粒要比表面平滑的微塑料颗粒更能引起免疫反应[50]。

3.6 基因与遗传毒性

微塑料还会影响生物机体的基因表达,并产生遗传毒性。基因组学的研究结果显示,微塑料暴露可改变牡蛎生殖细胞和卵母细胞的基因表达[24]。与对照组相比,暴露在微塑料中的日本青鳉鱼雌性个体多个基因表达显著下调[98]。暴露在聚苯乙烯微塑料中的紫贻贝(*Mytilus galloprovincialis*)有上千个基因表达异常[90]。有研究推断,导致基因表达异常可能与机体的能量分配有关,能量中断会导致编码胰岛素信号通路相关蛋白如消化腺和生殖腺的基因出现下调[24]。还有研究进行了两代桡足类浮游动物对微塑料的暴露实验,结果表明,与对照组相比,0.5 μm 的聚苯乙烯微球未对母代的生存产生显著影响,但是却显著降低了子代的存活率[91],这说明微塑料存在潜在的遗传毒性。

4 微塑料与其他污染物的复合毒性

在海洋环境中,微塑料表面容易与其他不同类型污染物发生结合作用。研究显示,微塑料会从海洋环境中吸附一些疏水性持久性有机污染物,如多氯联苯、多溴联苯醚、有机氯农药、多环芳烃、石油烃、双酚 A 等[103-108],还会吸附一些重金属如铅、锌、铜、铬、镉等[109-111]。当微塑料颗粒与其他污染物通过吸附或其他表面反应作用结合到一起时,会成为其他污染物进入到生物组织和器官的载体,届时微塑料与化学污染物会对生物机体产生复合毒性效应[97]。例如微塑料与持久性有机污染物的复合体可导致日本青鳉鱼多个基因表达出现下调,并且雄性个体的生殖细胞出现了异常增殖现象[98],微塑料和持久性有机污染物复合污染还会明显损伤日本青鳉鱼的肝脏组织[97],而肝脏在机体异生物质代谢和解毒过程中起着核心作用,由此可见,微塑料暴露引起的毒性效应是化学污染物与微塑料共同作用结果。还有研究发现微塑料与多环芳烃的复合污染会降低鰕虎鱼(*Pomatoschistus microps*)乙酰胆碱酯酶(AChE)和异柠檬酸脱氢酶(IDH)的活性,增加鱼类种群的死亡风险[94]。微塑料与多环芳烃复合暴露会增强多环芳烃在紫贻贝体内的生物效应,包括免疫反应、氧化应激反应、神经毒性效应、基因毒性等[90]。聚乙烯微塑料与六价铬[Cr(VI)]复合污染对稚鱼期鰕虎鱼的短期毒性实验结果表明微塑料与重金属复合污染也可对机体产生复合毒性[96]。聚乙烯微塑料颗粒和Cr(VI)单一胁迫未发现机体产生脂质过氧化,但是二者复合作用下机体的脂质过氧化水平显著升高;此外,单一Cr(VI)胁迫不会抑制幼鱼 AChE 的活性,单一聚乙烯微塑料暴露下机体 AChE 活性的抑制率为 21%,而复合暴露下机体 AChE 活性的抑制率可达到 31%,表现出明显的复合毒性[96]。

5 研究展望

海洋塑料垃圾问题早在 20 世纪 70 年代就受到科研人员的关注,当时在海洋生物体内也已发现有塑料存在。近年来,海洋塑料垃圾污染得到国际社会的高度关注。美国学者 2015 年发表的一项研究估算出 2010 年全球 192 个沿海国家和地区共产生塑料垃圾 2.75 亿 t,其中有 480 万吨到 1270 万 t 进入海洋,而这个数量还在持续增加[112]。联合国环境规划署(UNEP)的相关报告中指出,海洋中大量塑料垃圾对海洋生物生存的威胁日益加剧[9-10]。微塑料粒径较小,在海洋环境中数量巨大,易被海洋生物摄入体内,或附着在其表面,不但会对海洋生物的生存造成严重威胁,还可能引发大规模的海洋生态风险。因此,微塑料污染对海洋生物和生态系统造成的生态效应和健康风险成为当前海洋微塑料污染研究的核心内容[26]。有研究结果显示,我国每年排入海洋的塑料碎片垃圾重量在 132 万 t 至 353 万 t 之间,被认为是全球产生海洋塑料碎片最多的国家[112]。而目前,我国对海洋微塑料污染的关注度不高,对海洋微塑料污染所引发的生态问题缺乏认识。建议未来的研究应重点关注以下几方面内容:

(1)我国海洋环境中微塑料的污染现状及生物摄入状况研究。与国际相比,我国学界和政府部门对海洋微塑料污染的认识程度不够,有关微塑料的调查研究十分有限,对我国管辖海域的微塑料污染现状及引发的

生态效应缺乏了解。因此,应加强我国管辖海域不同功能区海洋环境及生物体中微塑料的数量、类型、尺寸等参数的调查,解析我国海域微塑料污染特征,为我国海洋生态环境保护提供科学依据,并且在国际交流和相关国际法规的制定过程中掌握主动权。

(2)微塑料的生物效应及其毒理学机制研究。与化学污染物和纳米颗粒物相比,微塑料的生物效应和致毒机理较为特别,其材质类型、尺寸(粒径)大小、表面形态、暴露剂量等均会影响其毒性效应。微塑料对生物体不仅会产生化学毒性,还会产生物理伤害。目前有关微塑料的生物效应和致毒机理研究结果还不一致,研究数据不够全面。因此,需要建立微塑料毒性数据库,通过毒性实验研究获得基本毒理学数据,为微塑料环境基准值的判定及标准制定提供基础资料。另外,还需要研究微塑料在生物体内的生物转运过程和代谢过程,及其与生物大分子的相互作用机制,从细胞和分子水平揭示微塑料的致毒机理。

(3)微塑料与我国海洋环境中常见化学污染物的复合效应研究。微塑料的表面特性使得其易与其他化学污染物发生相互作用,改变二者原有的生物效应。研究微塑料与其他化学污染物的相互作用机制及其对生物体的复合毒性效应,探讨微塑料在复合作用过程中所扮演的角色,将进一步掌握微塑料在海洋环境中的毒理学效应。

(4)微塑料在海洋生态系统中的作用及其生物地球化学行为。微塑料在海洋环境中数量巨大,并且可随海洋动力过程进行多维度迁移,要全面掌握微塑料在海洋环境中的生态效应,探讨海洋环境中微塑料的环境行为及其生态效应,仅靠生态学和生物学的研究是不够的,还必须进行多学科交叉研究。比如,从生物地球化学角度考虑生物体附着在微塑料颗粒表面后的沉降作用对全球碳循环的影响;结合物理海洋学探讨微塑料在全球不同海域之间的迁移规律,探索利用海洋遥感手段监测大范围海洋微塑料污染的可行性,应对微塑料迁移过程中带来的生物入侵问题和海洋微塑料污染的国际责任问题。

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